Wisconsin Department of Natural Resources

GLOBAL POSITIONING SYSTEM (GPS) ACCURACY REPORT

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This document and DNR's ***Comparing Global Positioning System (GPS) Tools*** are both available for downloading via the Internet:
http://www.dnr.state.wi.us/org/at/et/geo/location/gps_info.html

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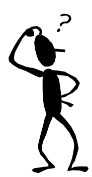
I. BACKGROUND INFORMATION

1. **ABOUT THIS DOCUMENT**

The use of global positioning system (GPS) tools continues to increase among Wisconsin Department of Natural Resources (DNR) programs, their partners, and the general public. And, as the number of users continues to grow, so does the need for support, guidance, and standards to help them select and use GPS tools that will adequately support their business needs, and collect GPS data that will integrate with DNR's geographic information system (GIS) data and applications.

Most DNR staff use recreational or mapping/resource grade GPS tools for their data collection activities. This document summarizes the results of a statistical analysis of the positional accuracy of data collected with several recreational and mapping/resource grade GPS receivers widely used by DNR programs. The primary goal of this study was to provide DNR program staff with general guidance about many of their most frequently asked GPS accuracy questions. These questions relate to one of the following topics:



- Data accuracy versus the number of coordinate readings collected for a feature.
- If/how GPS data should be differentially corrected.
- Customizing GPS software to export WTM91 (or other) coordinates directly.
- If the base station selected for differential correction affects GPS data accuracy.

We have attempted to make the contents of this document as applicable and practical as possible for DNR programs. For example, we used standard vendor software and procedures (i.e., the same used by many DNR programs) to post-process our mapping/resource grade GPS test data. And, while this document compares data accuracy results for specific recreational and mapping/resource grade GPS receivers, we do not intend to endorse any particular model or manufacturer.

Please refer to the document, *Comparing Global Positioning System (GPS) Tools*, (http://www.dnr.state.wi.us/org/at/et/geo/location/gps_info.html) for more general information about selecting the right GPS tools for your data collection project. This document, as well as copies of the Microsoft Excel spreadsheets containing the data we used for these analyses, can also be accessed via the same Internet page.

2. **ACKNOWLEDGEMENTS**

Authors: Robert Busch (GIS Analyst-DNR GIS Analysis and Mapping Service Section) and Lisa Morrison (GIS Data Specialist-DNR Enterprise Data Management Section). We would like to thank the following for their help with this study: Cody Cook (GIS Specialist-Wisconsin Department of Agriculture, Trade and Consumer Protection) for his help during data collection and for use of the Magellan 315 and Trimble GeoExplorer 2 receivers; Bill Smith (DNR Bureau of Endangered Resources) for use of the Garmin 12/12CX receivers and OziExplorer software; DNR Bureau of Parks and Recreation for use of their Trimble XR Pro receiver; Ron Ripp (Dane County Surveyor) for help in identifying viable NGS benchmarks; John Laedlein (GIS Data Specialist-DNR Enterprise Data Management Section) for help in analyzing the customized PathFinder Office WTM91 parameters; Mike Bohn (Chief-DNR Enterprise Data Management Section) for his advice and review during all phases of this project; Kenny Parsons (Chief-DNR Analysis and Mapping Services Section) for his general support of this project; and Ned Zuelsdorff and Jim VandenBrook (Department of Agriculture, Trade and Consumer Protection) for their general support of this project.

3. WHAT WAS NOT INCLUDED IN THIS GPS ACCURACY ASSESSMENT?

Although our study area was limited to a 30-mile radius around Madison, this document assumes that the results of our analyses can be generally extrapolated across Wisconsin. In addition, this test of GPS horizontal data accuracy did not include analyses or comparison of:

- "high end" land surveying grade GPS tools
- vertical data accuracy
- leaf-on versus leaf-off conditions
- different default (e.g., PDOP) values

4. GENERAL RECOMMENDATIONS

We recommend that DNR programs consider the information and conclusions in this document, along with information in the companion *Comparing Global Positioning System (GPS) Tools* document, to select recreational or mapping/resource grade GPS tools that adequately support their business needs. Specifically, the results of our analyses described in this document indicate that:

- DNR programs should collect the following number of readings per point feature to balance the number of readings collected in the field with the positional accuracy of the data.

  - 120 readings with a recreational grade receiver without real-time differential correction *(accuracy ≈ 10 meters)*.
  - 30 readings with a recreational grade receiver in real-time differential correction mode *(accuracy ≈ 10 meters)*.
  - 30 readings with a mapping/resource grade receiver with post-processing or real-time differential correction *(accuracy ≈ 4 meters)*.

- DNR programs should always differentially correct (i.e., using either post-processing or real-time techniques) data collected with mapping/resource grade GPS tools to take full advantage of the functionality and accuracy of these systems.

- No appreciable difference exists between the positional accuracy of data differentially corrected using post-processing versus real-time techniques.

- If using Trimble PathFinder Office software, DNR programs should load our customized parameter file to a desktop PC to export data (i.e., collected with a Trimble GPS receiver) directly into WTM91 coordinates.

- No appreciable difference exists between the positional accuracy of GPS data differentially corrected using data from different base stations, assuming the base station is operational during the data collection period and is within 100 miles of the data collection site. DNR programs should always verify the availability of a selected base station (i.e., for both post-processing and real-time differential correction) before going into the field!

II. TOOLS AND METHODS

1. GPS RECEIVERS TESTED AND NUMBER OF READINGS COLLECTED

TABLE 1 lists the two recreational and three mapping/resource grade receiver models used in this study. We used each of these receivers to collect data files containing *raw, uncorrected readings* (i.e., x-y coordinate pairs) for each selected National Geodetic Survey benchmark. We also used the Garmin 12CX and Trimble XR Pro in *real-time differential correction* mode to collect another set of data files at each of these benchmarks. After data collection, we used *post-processing differential correction* techniques to correct the raw mapping/resource grade GPS data. (The recreational grade receivers we tested did not have post-processing capabilities).

TABLE 1. Tested GPS Receivers and Number of Data Files Collected Per Benchmark.

GPS RECEIVER MODEL	GPS RECEIVER GRADE	DIFFERENTIAL CORRECTION	NUMBER OF DATA FILES COLLECTED PER BENCHMARK
Magellan 315	Recreational	Raw, uncorrected data	9 *(one per set of readings)*
Garmin 12/12CX	Recreational	Raw, uncorrected data	9 *(one per set of readings)*
		Real-time	9 *(one per set of readings)*
Trimble GeoExplorer 2	Mapping/Resource	Raw, uncorrected data	1 *(240 readings)*
		Post-processing	
Trimble GeoExplorer 3	Mapping/Resource	Raw, uncorrected data	1 *(240 readings)*
		Post-processing	
Trimble XR Pro	Mapping/Resource	Raw, uncorrected data	1 *(240 readings)*
		Post-processing	
		Real-time	1 *(240 readings)*

We then compared the GPS-derived coordinates to the coordinates provided by the National Geodetic Survey for each selected benchmark. As appropriate, we analyzed and compared the accuracy of raw versus post-processed data, raw data versus data collected in real-time differential correction mode, and, in the case of the XR Pro, data differentially corrected using both post-processing and real-time techniques.

Each GPS receiver data file contained a set of 1, 5, 10, 15, 30, 60, 120, 180, or 240 readings. The number of coordinate pairs per data file depended on whether the receiver was able to display the actual number of readings being collected in the field (as described for each receiver grade below).

A. Recreational Grade Receivers

Like most recreational grade GPS receivers, the tested units had no mechanism for determining the actual number of readings collected (and automatically averaged) in the field. These receivers displayed only the "averaged" *x-y* coordinate positions of benchmarks, and had no ability to store or download the discrete (i.e., raw, unaveraged) readings collected. We, therefore, used each receiver to collect nine individual data files, one for each set of readings (1, 5, 10, etc.), over specified time intervals. We <u>assumed that each receiver collected one reading per second</u>, so that the number of averaged readings equaled seconds of collection time (e.g., 5 seconds = 5 readings).

B. *Mapping/Resource Grade Receivers*

The mapping/resource grade receivers let us set the default data collection rate at one reading per second, and they displayed the actual number of readings collected (and automatically averaged) for each benchmark position. We were also able to use Trimble PathFinder Office software to subset one data file, containing 240 readings, into the nine individual data files (containing 1, 5, 10, etc. readings) for each benchmark position. Therefore, we collected data files of 240 readings using the mapping/resource grade receivers, avoiding the need to use collection time to determine the number of readings per data file (i.e., as required for the recreational grade receivers).

2. GPS RECEIVER DEFAULT SETTINGS

Whenever possible, default settings with the potential to affect the positional accuracy of the GPS data were standardized among the tested receivers (see ***TABLE 2***). In addition, all of the recreational grade receivers reported readings to at least one decimal second (precision ≈ 3 meters), while all tested mapping/resource grade receivers captured data to a sub-meter level of precision.

TABLE 2. GPS Receiver Default Settings.

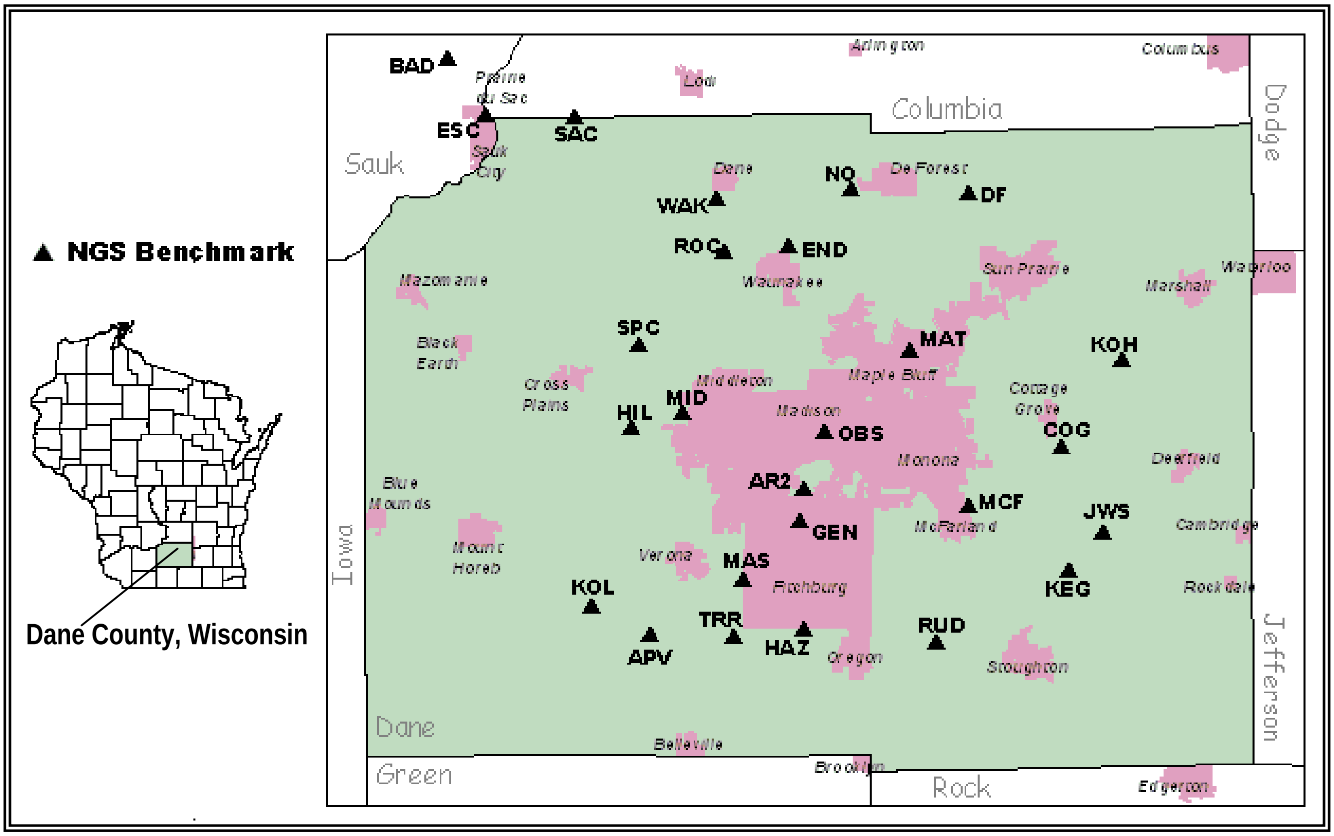
SETTING	DEFAULT VALUE	COMMENTS
Position Dilution of Precision (PDOP)	6	Set on all receivers. Data collection halted when PDOP was 6 or greater.
Raw Data Collection Rate	1 reading per second	Set on all mapping/resource grade receivers. Assumed for all recreational grade receivers.
Raw Data Coordinate System	Latitude/Longitude (*degrees, minutes, seconds*)	Set on all receivers ***except*** the Magellan 315, which collected Universal Transverse Mercator (UTM) coordinates.
Raw Data Collection Spheroid/Datum	World Geodetic System 1984 (WGS84) spheroid	Set on all receivers ***except*** the Magellan 315, which collected UTM coordinates referenced to the North American Datum of 1983 (NAD83) – Geodetic Reference System 1980 (GRS80) spheroid.
Elevation Mask Angle	15°	Set on all mapping/resource grade receivers. Assumed for all recreational grade receivers.

3. NATIONAL GEODETIC SURVEY BENCHMARKS

We used National Geodetic Survey (NGS) benchmarks for horizontal control points in this study. Specifically, we selected first-, second-, and third-order NGS benchmarks located within a 30-mile radius of Madison, Wisconsin (i.e., in Dane and Sauk Counties). We identified an initial group of 85 benchmarks meeting these criteria via the NGS website (http://www.ngs.noaa.gov/datasheet.html), and then selected 26 to be used in this study (see ***MAP 1*** and ***Appendix A***). These included 4 first-order benchmarks, 18 second-order benchmarks, and 4 third-order benchmarks.

We chose these 26 benchmarks based on two primary characteristics: (1) they were evenly distributed around Madison and (2) they were actually identifiable in the field (e.g., they had not been removed, damaged, buried, etc.). Although our minimum sample size was 21 benchmarks, we collected data at five additional benchmarks to ensure that any data collection problems (e.g., equipment failure, nearby obstacles) or data anomalies at a particular benchmark would not hinder our statistical analyses. However, we did experience technical problems with the real-time beacon receiver (GBR-21) for the Garmin 12CX, and were only able to collect data at 17 benchmarks using this receiver.

MAP 1. Locations of NGS Benchmarks Used in this Study.



Once we found a benchmark in the field, we verified its identification using the NGS data sheet. We then sketched a "Sky Plot", indicating the position of obstructions 15° or more above the horizon around the benchmark (see *GPS Accuracy Test Data Sheet* in ***Appendix B***). We used an inclinometer to record the angle of an obstacle above the horizon, and a compass to measure the general direction of obstacles from the benchmark.

4. FIELD EQUIPMENT SET-UP

Whenever possible, equipment set-up and data collection methods were standardized among the five tested GPS receivers. We reviewed base station availability and satellite almanac data before going into the field in order to optimize our data collection activities.

We completed one *GPS Accuracy Test Data Sheet* (see ***Appendix B***) at each benchmark. In addition to the Sky Plot mentioned above, this form contained (1) the NGS identification number and description of the benchmark, (2) data collection date, (3) general weather conditions present during data collection, (4) data collection start and stop times for each receiver, and (5) additional comments. We used the data on these data sheets to help document our data collection process and to explain anomalous results, as appropriate.

A tripod was centered and leveled over each benchmark. Each GPS receiver was allowed to initialize before collecting data. We placed most of the receivers on the tripod sequentially (usually starting with the recreational grade units and ending with the Trimble XR Pro) and collected data using the methods described below. In some cases, however, we were able to collect data at a benchmark using two receivers simultaneously. All the data files for a benchmark position were collected in about 30 minutes in most cases.

5. DATA COLLECTION METHODS

A. Collecting Recreational Grade GPS Data

As described above, we assumed that the number of readings equaled the seconds of collection time (e.g., 5 seconds = 5 readings) for the recreational receivers. We used a digital wristwatch to measure 1, 5, 10, 15, 30, 60, 120, 180, and 240 second intervals, resulting in the three sets of nine data files listed in ***TABLE 1***.

B. Collecting Mapping/Resource Grade GPS Data

We used the mapping/resource grade receivers to collect four data files containing 240 readings each (see ***TABLE 1***). We later subset them into separate data files containing, as described below.

C. Downloading GPS Data

Field data on each receiver was downloaded to a PC at the end of each collection day. We used OziExplorer software to download Garmin 12/12CX data and export it in .dbf format. We used Trimble PathFinder Office software (version 2.7) to download data from the mapping/resource grade receivers for further processing (described below). We did not have access to file management software for the Magellan 315, so we typed these data into a Microsoft Excel spreadsheet.

6. PREPARING GPS DATA FOR POST-PROCESSING AND ANALYSES

A. Parsing Mapping/Resource Grade GPS Data

We used Trimble PathFinder Office software (i.e., *SSF Record Editor* utility) to delete readings outside the benchmark, and parse (or subset) each data file of 240 readings into nine separate files containing 1, 5, 10, etc. readings. The readings in each subset file began with the first *x-y* coordinate pair in the "parent" data file plus the specified number of subsequent readings. We believe that parsing the files in this way provides a more realistic analysis of data accuracy <u>based on the way DNR programs use GPS tools in the field and process data back in the office</u>! These comma-delimited files were then used for post-processing and other analyses as described below.

B. Projecting Recreational GPS Data into WTM91 Coordinates

We used DNR's standard GIS-based (i.e., ArcInfo) 3-step process to project the UTM and latitude/longitude readings from the recreational grade receivers into Wisconsin Transverse Mercator coordinates referenced to the 1991 adjustment of the North American Datum of 1983 –

GRS80 spheroid. These are commonly referred to as WTM91 coordinates, and are DNR's standard for internal geographic information system (GIS) applications. This projection process resulted in tab-delimited text files.

7. POST-PROCESSING DIFFERENTIAL CORRECTION METHODS

We used Trimble PathFinder Office software to differentially correct raw data for all mapping/resource grade receivers used in this study. Correction data was downloaded from the closest operational NGS "Continuously Operating Reference Stations" (CORS) base station via the Internet (http://www.ngs.noaa.gov/CORS/), except when we tested the effects of base station selection on GPS data accuracy (described in ***Section III.5*** below). ***Appendix D*** identifies the specific CORS stations used for various analyses conducted as part of this study.

We then loaded customized datum parameters (see ***Section III.4***) into Trimble PathFinder Office software to convert and export latitude/longitude coordinates (referenced to the WGS84 spheroid) collected using the mapping/resource grade receivers into WTM91 coordinates.

III. HORIZONTAL GPS DATA ACCURACY ANALYSES RESULTS

1. GENERAL METHODS

We referred to the Minnesota Land Management Information Center's *Positional Accuracy Handbook* (1999) for general guidance in conducting our analyses. That document describes procedures for testing the accuracy of horizontal positional data, and contains a "Horizontal Accuracy Statistics Worksheet" (see ***Appendix C***) to help users set up appropriate data tables for statistical analyses. It also provides example GPS horizontal data accuracy assessments from several sources. We built a "Horizontal Accuracy Statistics Worksheet" template worksheet in Microsoft Excel, and imported each of our data sets into this worksheet (or copies of it) to conduct our various analyses.

> While the results of the data accuracy analyses described in this document are specific to the GPS dataset that we collected and tested, we are confident that they can be generally extrapolated across Wisconsin, assuming the same GPS receivers, software, and data collection and processing methods are used. **To follow best practice, the positional accuracy of features within a particular dataset should always be determined independently!**

2. GPS DATA ACCURACY AND NUMBER OF READINGS

DNR programs often ask how the number of readings collected for a feature relates to the positional accuracy of that feature's location. Time spent collecting data in the field is an important workload consideration for most DNR programs, because they must balance field time with other time requirements (e.g., data processing and management) for a specific project. This section compares the accuracy of nine sets of readings collected with each receiver (and differentially corrected, as appropriate) at 21 different NGS benchmarks.

A. *Methods*

We built a Microsoft Excel template based on the "Horizontal Accuracy Statistics Worksheet" (***Appendix C***) to generate summary statistics for each set of readings (1, 5, 10, 15, 30, 60, 120, 180, and 240) for each receiver at each benchmark. All available raw and differentially corrected data for all receivers were included in this analysis.

We initially attempted to average data from the same 21 benchmarks for each tested receiver, but due to data collection problems or other errors, we needed to use data from one or more of the "extra" benchmarks in some cases. ***Appendix A*** lists the specific benchmarks used in this analysis. The same CORS base station (i.e., Blue River, Wisconsin – BLRW) was used to differentially correct (i.e., both post-processing and real-time) all the GPS data used in this analysis (see ***Appendix D***).

B. *Discussion of Results*

GRAPH 1 (***Appendix E***) compares the average accuracy trend lines (within a 95% confidence level) of each of the five receivers for each set of readings. ***GRAPH 2*** (***Appendix E***) shows the same trend lines for just the mapping/resource grade receivers from ***GRAPH 1***. Summary statistics, including root mean square (RMS) error, 95% confidence interval, and standard deviation for all of the tested receivers are shown in ***TABLE 3*** (***Appendix E***). These graphs and summary statistics clearly illustrate the following conclusions:

<u>Recreational Grade Receivers</u>

- GPS data collected with recreational grade receivers was less accurate than data collected using mapping/resource grade receivers – except in the case of the Garmin 12CX once approximately 120 readings were collected in real-time differential correction mode.

- Garmin 12CX real-time differentially corrected data were actually less accurate than raw data until 10 - 15 readings were collected, after which the accuracy of 12CX data was better than the accuracy of the raw data collected with the Garmin 12.

<u>Mapping/Resource Grade Receivers</u>

- Raw data for all of the mapping/resource grade receivers had an average accuracy of better than 8 meters, regardless of the number of readings collected.

- Differentially corrected mapping/resource grade GPS data were more accurate than raw data collected using these same receivers. The average accuracy of differentially corrected data was between 1.5 - 5 meters (the advertised accuracy of these units!), which was approximately 3 – 4 meters more accurate than the raw data.

- In all cases, the RMS error, confidence interval, and standard deviation for a particular number of readings were smaller for differentially corrected mapping/resource grade GPS data, than for the raw data collected with these units. This indicates that differentially corrected mapping/resource grade GPS data are considerably more accurate than raw data.

C. Recommendations

A DNR program should use the positional accuracy results from this test, in conjunction with information in the *Comparing Global Positioning System (GPS) Tools* document, to select a recreational or mapping/resource grade receiver that adequately supports its business needs. Many DNR programs currently instruct staff to collect 120 readings per feature with mapping/resource grade receivers. The results of this analysis, however, indicate that DNR programs consider collecting:

- 120 readings per point feature with recreational grade receivers without real-time correction to ensure that the positional accuracy of the raw data is consistently around 10 meters.
- 30 readings per point feature with recreational grade receivers in real-time mode to ensure that the positional accuracy of the corrected data is consistently around 10 meters.
- 30 readings per point feature with mapping/resource grade receivers to ensure that the positional accuracy of the corrected data is consistently 4 meters or better.

3. GPS DATA ACCURACY AND DIFFERENTIAL CORRECTION

One important consideration in selecting an appropriate receiver for a particular data collection project is whether the program requires its GPS data to be differentially corrected, and by which method (i.e., post-processing or real-time). The *Comparing Global Positioning System (GPS) Tools* document discusses general differences between and uses of post-processing and real-time techniques. We compared the positional accuracy of raw and differentially corrected datasets collected with the same receiver. We also compared the positional accuracy of Trimble XR Pro data differentially corrected using both post-processing and real-time techniques.

A. Methods

The same methods and data described in ***Section III.2*** were used to complete this series of tests, including use of the CORS base station in Blue River, Wisconsin for both post-processing and real-time differential correction of all data. ***Appendix A*** lists the benchmarks used in this analysis.

B. Discussion of Results

We used the same results described in ***Section III.2*** (and presented in ***GRAPH 1***, ***GRAPH 2***, and ***TABLE 3*** in ***Appendix E***) to develop our differential correction recommendations described below.

C. Recommendations

Differential correction, using either post-processing or real-time techniques, substantially increases the positional accuracy of recreational and mapping/resource grade GPS data. Based on the results of this analysis, we recommend that DNR programs should:

- Decide to use a recreational grade receiver in real-time differential correction mode based on (1) the number of readings (i.e., time spent in the field) versus the program's required data accuracy and (2) the specific data collection functionality needs of the program.

- Always differentially correct mapping/resource grade GPS data to take full advantage of the functionality and accuracy of these systems.

- Decide to use post-processing versus real-time differential correction techniques based on factors other than the positional accuracy of the data. Our tests indicate that both methods produce corrected mapping/resource grade GPS data with very similar data accuracy. Using a GPS receiver with real-time differential correction capabilities may be more flexible because, if the real-time beacon receiver malfunctions or cannot lock on to an appropriate base station, the GPS data can still be post-processed using data from another base station at a later date.

4. GPS DATA ACCURACY AND CUSTOMIZED WTM91 CONVERSION PARAMETERS

Converting GPS readings into WTM91 coordinates for use with other DNR GIS data and applications can be a significant workload for staff. Trimble PathFinder Office software can be customized to project and download GPS data directly in WTM91 coordinates. This has the potential to simplify data conversion, saving time and resources by eliminating the need to acquire/access ArcInfo software and project coordinates using DNR's standard GIS-based 3-step process. This section compares the accuracy of benchmark positions converted to WTM91 using the customized parameters in PathFinder Office versus those projected using the traditional 3-step ArcInfo projection process.

A. *Methods*

We used only Trimble GeoExplorer 3 data for this analysis, because this GPS receiver model has the greatest number of current and potential users within DNR. We also assumed that there would be no substantial difference between the GeoExplorer 3 results and the results of this same analysis based on "higher end" Trimble XR Pro receiver data. Recall that the GeoExplorer 3 readings were originally collected as latitude/longitude degrees, minutes, and decimal seconds referenced to the WGS84 spheroid.

First, Trimble GeoExplorer 3 data collected at 21 benchmarks (see ***Appendix A*** for specific benchmarks used in this analysis) were post-processed using the CORS base station at Blue River, Wisconsin (BLWR) and standard techniques described in ***Section II.7***. We loaded the customized parameters into PathFinder Office, and then converted and exported these readings directly into WTM91 coordinates.

We then used DNR's standard 3-step process to project the same post-processed GeoExplorer 3 readings into WTM91 coordinates. These WTM91 coordinates were used as the "control" for this analysis, because this 3-step process is DNR's current standard for coordinate projection. We loaded the WTM91 coordinates from both processes into a template based on the "Horizontal Accuracy Statistics Worksheet" (***Appendix C***) to generate summary statistics for the two projection methods.

B. Discussion of Results

TABLE 4 indicates that no substantial difference exists between the accuracy of data generated using the current standard 3-step coordinate projection process versus loading the customized parameters in PathFinder Office software. We believe this is because the Trimble and ArcInfo software both use a similar algorithm to project coordinates.

TABLE 4. Summary Statistics for Trimble PathFinder Office WTM91 Conversion Parameters.

Trimble GeoExplorer 3		
RMS Error (meters)	**95% Conf. Interval (meters)**	**Standard Deviation (meters)**
0.0006	0.0011	0.0000

C. Recommendations

Based on our analysis, we recommend that DNR programs *using the tested Trimble products* load the customized parameter file, and download GeoExplorer 2, GeoExplorer 3, and XR Pro data directly into WTM91 coordinates using PathFinder Office software. The custom WTM91 parameter file and instructions for loading it on to a desktop PC with PathFinder Office software are found on DNR's Intranet at: http://int/at/et/geo/location/trimble_wtm91.html.

5. **GPS DATA ACCURACY AND BASE STATION SELECTION**

DNR programs also commonly ask if the base station they select for post-processing or real-time differential correction purposes affects the accuracy of their GPS data. We tested the accuracy of GPS data collected using one receiver and post-processed using correction data from several different base stations.

A. Methods

We used only Trimble GeoExplorer 3 data for this analysis, because this GPS receiver model has the greatest number of current and potential users within DNR. We also assumed that there would be no substantial difference between the GeoExplorer 3 results and the results of this same analysis based on "higher end" Trimble XR Pro receiver data. We also used data files containing 30 readings, the number of readings (per point feature) that we recommend collecting with the GeoExplorer 3.

The 30-reading raw GeoExplorer 3 data files collected at 21 benchmarks (see ***Appendix A*** for specific benchmarks used in this analysis) were each post-processed using seven different CORS base stations (see ***Appendix D*** for specific base stations used in this analysis) and standard techniques described in ***Section II.7***. We then converted and exported the post-processed readings directly into WTM91 coordinates using Trimble PathFinder Office software (described in ***Section III.4*** above). Finally, we loaded these WTM91 coordinates into a template based on the "Horizontal Accuracy Statistics Worksheet" (***Appendix C***) to generate summary statistics.

B. Discussion of Results

TABLE 5 shows that no substantial difference exists in the accuracy of GeoExplorer 3 data post-processed using correction data from these seven CORS base stations. Additional analyses would be required to quantify further the effects of base station selection on GPS data accuracy.

TABLE 5. Summary Statistics for CORS Base Station Test.

Trimble GeoExplorer 3: 30-reading data files				
NGS CORS PID	**RMS Error (meters)**	**95% Conf. Interval (meters)**	**Standard Deviation (meters)**	**Approximate Distance from Madison, WI**
AI2149	2.45	4.24	1.09	58 miles
AA8061	2.41	4.17	1.09	78 miles
AA3921	2.93	5.07	1.07	144 miles
AE2268	3.32	5.75	1.05	84 miles
AI2153	2.63	4.54	1.19	236 miles
AA8057	2.72	4.71	1.34	160 miles
AH5611	2.74	4.74	1.34	198 miles
*	2.81	4.87	1.49	251 miles

C. Recommendations

Based on the results of this analysis, we recommend DNR programs:

- Use the CORS base station closest to the GPS data collection site/area, if the data will be differentially corrected using post-processing or real-time techniques. (Most GPS receivers with real-time differential correction capabilities automatically scan for the closest available base station.)

- Use the same CORS base station (if available) to post-process data that are collected at the same site/area over a period of months or even years.

- All CORS base stations are unavailable at one time or another for routine maintenance, etc., and some are not set-up to transmit and record data continuously. It is the responsibility of the user to determine if the selected base station was in operation while GPS data were being collected. ***Appendix F*** describes the process for checking CORS base station availability.

IV. REFERENCES

Garmin GPS Products - http://www.garmin.com/products/

Magellan (Ashtech) GPS Products –http://www.ashtech.com/

Minnesota Land Management Information Center. 1999. *Positional accuracy handbook*. St. Paul, Minnesota. (💻 http://www.mnplan.state.mn.us/press/accurate.html)

National Geodetic Survey Continuously Operating Reference Stations (CORS) - http://www.ngs.noaa.gov/CORS/

National Geodetic Survey Benchmark Data Sheets - http://www.ngs.noaa.gov/datasheet.html

OziExplorer software - http://www.oziexplorer.com/

Trimble GPS Products - http://www.trimble.com/products/

V. APPENDICES

Appendix A lists general information about our data collection activities, and the NGS benchmarks used in these GPS data accuracy analyses.

Appendix B contains a copy of the "GPS Accuracy Test Data Sheet" we filled out at each NGS benchmark.

Appendix C contains a copy of the "Horizontal Accuracy Statistics Worksheet Template" from *Positional Accuracy Handbook* (Minnesota Land Management Information Center, 1999).

Appendix D lists the NGS Continuously Operating Reference Station (CORS) base stations used to differentially correct data used in these analyses.

Appendix E contains ***GRAPH 1***, ***GRAPH 2*** and ***TABLE 3***.

Appendix F describes the process for checking CORS base station availability.

APPENDIX A: NATIONAL GEODETIC SURVEY (NGS) BENCHMARKS USED IN THIS STUDY

DNR CODE	NGS PID	USGS 7.5' QUAD NAME	ORDER	GPS DATA COLLECTION DATE	WEATHER CONDITIONS	USED IN RECEIVER* ANALYSES	COMMENTS
APV	NH1622	Verona	2nd	10/09/2000	Clear (≈ 7% overcast)	1, 2, 4, 5, 6, 7	No Garmin 12CX data. Isolated obstacles (trees, building, sign) 17°-30° above horizon in northeast and southeast quadrants.
AR2	OM1235	Madison West	2nd	09/28/2000	Clear sky	all receivers	Isolated obstacles 16°-18° above horizon in northwest quadrant.
BAD	OM1179	Sauk Prairie	1st	10/10/2000	Clear - 60°F	all receivers	Isolated utility pole 21° above horizon to the north.
COG	OM1230	Cottage Grove	2nd	10/06/2000	Clear - 43°F (≈ 3% overcast)	all receivers	No Garmin 12CX data. Isolated obstacles (trees, utility poles) 21°-56° above horizon in all but southwest quadrant.
DF	OM1059	DeForest	2nd	09/25/00	Clear - 60°F	1, 4, 5, 6, 7	Continuous trees 74°-86° above horizon in northeast quadrant, and 20°-30° above horizon in southwest and southeast quadrants.
END	OM0647	Waunakee	2nd	10/02/2000	Partly cloudy (≈ 50% overcast)	all receivers	Benchmark located on top edge of a quarry wall, and may have moved eastward due to quarry work.
ESC	OM0472	Sauk City	1st	10/09/2000	Clear - 65°F	all receivers	Continuous trees and utility poles 19°-77° above horizon in all but southeast quadrant.
GEN	OM1237	Madison West	2nd	09/28/2000	Clear	all receivers	Isolated obstacles 20°-57° above horizon in all but northwest quadrant.
HAZ	NH1624	Oregon	2nd	10/09/2000	Clear - 60°F	1, 2, 4, 5, 6, 7	No Garmin 12CX data. Continuous trees 20°-55° above horizon in northeast quadrant. Isolated trees 20°-35° above horizon in northwest and southwest quadrants.
HIL	OM1152	Middleton	2nd	09/28/2000	Clear - 68°F	2, 3	Clear sky. Continuous trees 20°-52° above horizon in northeast quadrant. Isolated trees 20°-40° above horizon in all other quadrants.
JWS	OM1240	Cottage Grove	2nd	10/06/2000	Clear - 47°F	all receivers	Power problem with GeoExplorer 3. Isolated trees 22°-52° above horizon in northeast and southeast quadrants. Utility pole 87° above horizon in northeast quadrant.
KEG	NH1630	Stoughton	2nd	10/09/2000	Clear - 47°F	2, 3	Isolated trees, utility poles, and buildings 20°-86° above horizon in all quadrants.
KOH	OM1046	Cottage Grove	3rd	10/10/2000	Clear - 55°F	all receivers	Clear sky. Utility pole 97° above horizon to the north.
KOL	NH1578	Mt. Vernon	1st	10/09/2000	Clear - 65°F	1, 2, 4, 5, 6, 7	No Garmin 12CX data. Trees 20° above horizon to the north. Utility pole 60° above horizon in southwest quadrant.
MAS	NH0938	Oregon	2nd	10/09/2000	Clear (≈ 10% overcast)	1, 2, 4, 5, 6, 7	No Garmin 12CX data. Utility poles 20°-35° above horizon in northeast and southwest quadrants.

* **1** = Magellan 315; **2** = Garmin 12; **3** = Garmin 12CX (real-time); **4** = GeoExplorer 2; **5** = GeoExplorer 3; **6** = Trimble XR Pro; **7** = Trimble XR Pro (real-time)

APPENDIX A: NATIONAL GEODETIC SURVEY (NGS) BENCHMARKS USED IN THIS STUDY (continued)

DNR CODE	NGS PID	USGS 7.5' QUAD NAME	ORDER	GPS DATA COLLECTION DATE	WEATHER CONDITIONS	USED IN STATS FOR RECEIVER*	COMMENTS
MAT	OM1219	DeForest	2nd	09/25/00	Partly cloudy	no receivers	Continuous trees and buildings 20°-30° above horizon in southeast quadrant and portions of northeast quadrant.
MCF	OM1076	Madison East	3rd	09/25/00	Partly cloudy – 45°F	1, 4, 5, 6, 7	Isolated trees and water tower 20°-52° above horizon in northeast and southeast quadrants.
MID	OM0612	Middleton	2nd	09/28/2000	Clear - 70°F	1, 2, 3, 5, 6, 7	Power lines directly overhead, and benchmark directly adjacent to a metal fence (e.g., potential multi-path errors?). Continuous trees up to 80° above horizon in northwest quadrant. Isolated trees and utility poles 18°-45° above horizon in southwest and southeast quadrants.
NO	OM1104	Waunakee	3rd	09/25/00	Clear	1	Utility poles 17° above horizon to the south and 90° above horizon to the north.
OBS	OM0650	Madison West	2nd	09/28/2000	Partly cloudy – 50°F	all receivers	Continuous trees 20°-70° above the horizon in the southwest and southeast quadrants.
ROC	OM0651	Springfield Corners	1st	10/02/2000	Clear (≈ 5% overcast)	all receivers	Continuous trees 21°-49° above horizon in southwest quadrant. Isolated trees 25°-46° above horizon in northwest and northeast quadrants.
RUD	NH1618	Rutland	2nd	10/09/2000	Clear - 57°F	all receivers	Garmin 12CX power failure at 60 readings. Continuous trees up to 45° above horizon in northwest and northeast quadrants. Isolated trees and utility poles 10°-25° above horizon in southwest and southeast quadrants.
SAC	OM0637	Sauk City	2nd	10/09/2000	Clear - 60°F	all receivers	Trees 42°-45° above horizon in northeast and southeast quadrants. Utility poles 18°-35° above horizon in southwest and southeast quadrants.
SPC	OM0630	Springfield Corners	2nd	10/02/2000	Cloudy (≈ 70% overcast)	2, 3, 4	Corn 20° above horizon to the east.
TRR	NH0446	Oregon	2nd	10/09/2000	Clear - 68°F (≈ 15% overcast)	1, 2, 4, 5, 6, 7	No Garmin 12CX data on 10/09/00, recollected on 11/17/00. Tree stands 17°-33° above horizon in all quadrants.
				11/17/2000 *Garmin 12CX*	Light snow - 32°F		
WAK	OM1150	Waunakee	3rd	10/02/2000	Cloudy (≈ 90% overcast)	2, 3, 4, 5, 6, 7	Power problem with GeoExplorer 2. Utility pole 45° above horizon to the north and 35° above horizon to the west. Corn 22° above horizon in northwest and southwest quadrants.

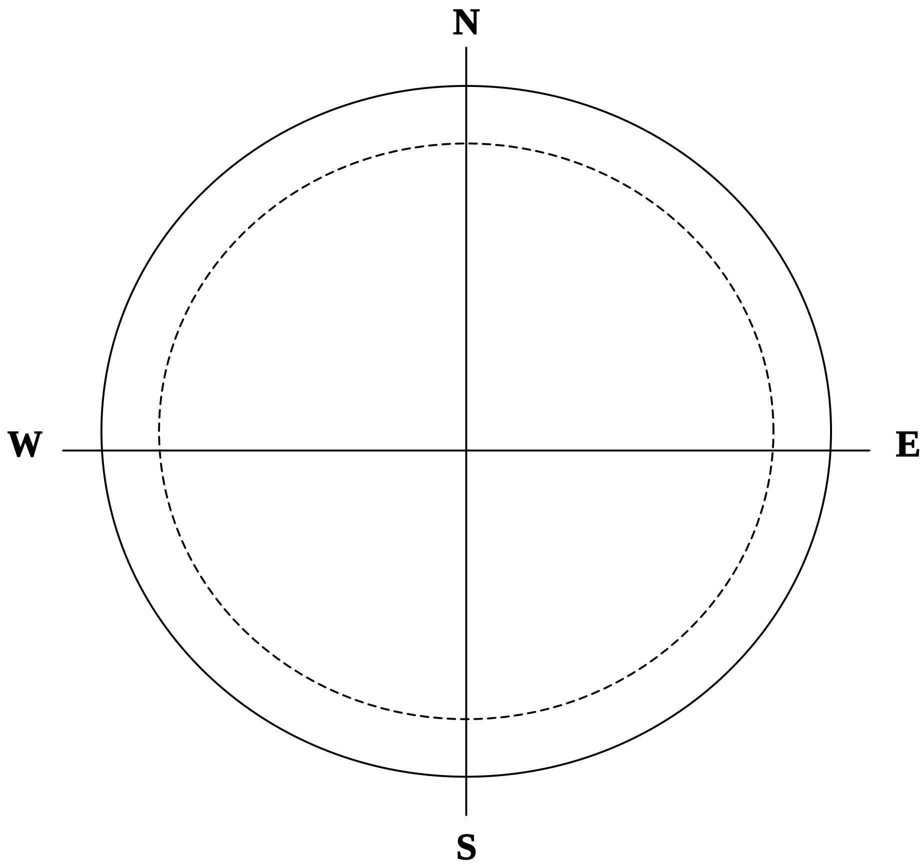
* **1** = Magellan 315; **2** = Garmin 12; **3** = Garmin 12CX (real-time); **4** = GeoExplorer 2; **5** = GeoExplorer 3; **6** = Trimble XR Pro; **7** = Trimble XR Pro (real-time)

APPENDIX B: GPS ACCURACY TEST DATA SHEET

NGS Site ID and Description: ***Date:***

Weather Conditions:

Sky Plot (complete for obstructions higher than 15° mask):



Data Collection Times:

RECEIVER	*START TIME*	*END TIME*
Magellan 315 (raw data)		
Garmin 12 (raw data)		
Garmin 12CX (real-time)		
Trimble GeoExplorer 2 (raw data)		
Trimble GeoExplorer 3 (raw data)		
Trimble GeoExplorer XR Pro (raw data)		
Trimble GeoExplorer XR Pro (real-time)		

Additional Comments (use back of form): ➔➔➔➔➔➔➔➔➔➔➔➔➔➔➔➔➔➔➔

APPENDIX C. HORIZONTAL ACCURACY STATISTICS WORKSHEET TEMPLATE.

Source: *Positional Accuracy Handbook* (Minnesota Land Management Information Center, 1999)

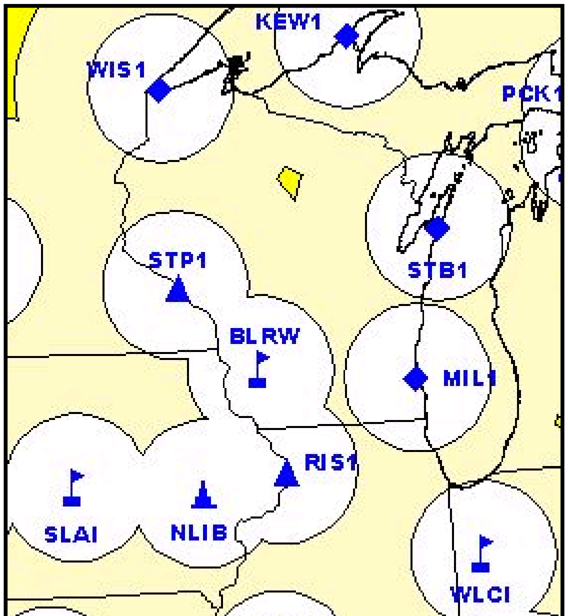
Figure 4. Horizontal accuracy statistic worksheet.

A Point number	B Point description	C x (independent)	D x (test)	E diff in x	F (diff in x) ^{2}	G y (independent)	H y (test)	I diff in y	J (diff in y) ^{2}	K (diff in x) ^{2} + (diff in y) ^{2}
								sum	
								average	
								$RMSE_r$	
								NSSDA	

Column	Title	Content
A	Point number	Designator of test point
B	Point description	Description of test point
C	x (independent)	x coordinate of point from independent data set
D	x (test)	x coordinate of point from test data set
E	diff in x	x (independent) - x (test)
F	(diff in x) ^{2}	Squared difference in x = (x (independent) - x (test)) ^{2}
G	y (independent)	y coordinate of point from independent data set
H	y (test)	y coordinate of point from test data set
I	diff in y	y (independent) - y (test)
J	(diff in y) ^{2}	Squared difference in y = (y (independent) - y (test)) ^{2}
K	(diff in x) ^{2} + (diff in y) ^{2}	Squared difference in x plus squared difference in y = (error radius) ^{2}
	sum	$\sum$ [(diff in x) ^{2} + (diff in y) ^{2}]
	average	sum / number of points
	$RMSE_r$	Root Mean Square Error (radial) = average $^{1/2}$
	NSSDA	National Standard for Spatial Data Accuracy statistic = 1.7308 * $RMSE_r$

APPENDIX D: CORS BASE STATIONS USED FOR SPECIFIC ANALYSES.

Information about Continuously Operating Reference Stations (CORS), including maps and downloadable correction data files are found on the NGS website: http://www.ngs.noaa.gov/CORS/.



Source: National Geodetic Survey website
http://www.ngs.noaa.gov/CORS/

White circles around the CORS sites represent the 100 kilometer (≈ 62 mile) range of the base station. The 200 and 300 kilometer ranges are also shown. A small diamond-shaped portion of north central Wisconsin has no CORS coverage within 300 kilometers (≈ 186 miles). Both real-time and post-processing differential correction of GPS data in this area, as well as any part of Wisconsin where radio signals may be blocked by terrain (e.g., the "Driftless Area" in the southwest) or other obstacles, may be more problematic.

0 100 200 300
(kilometers)

The following NGS CORS base station was used for post-processing and real-time differential correction of all data used in the following analyses: GPS Data Accuracy and Number of Readings (***Section III.2***), GPS Data Accuracy and Differential Correction (***Section III.3***), and GPS Data Accuracy and Customized WTM91 Conversion Parameters (***Section III.4***).

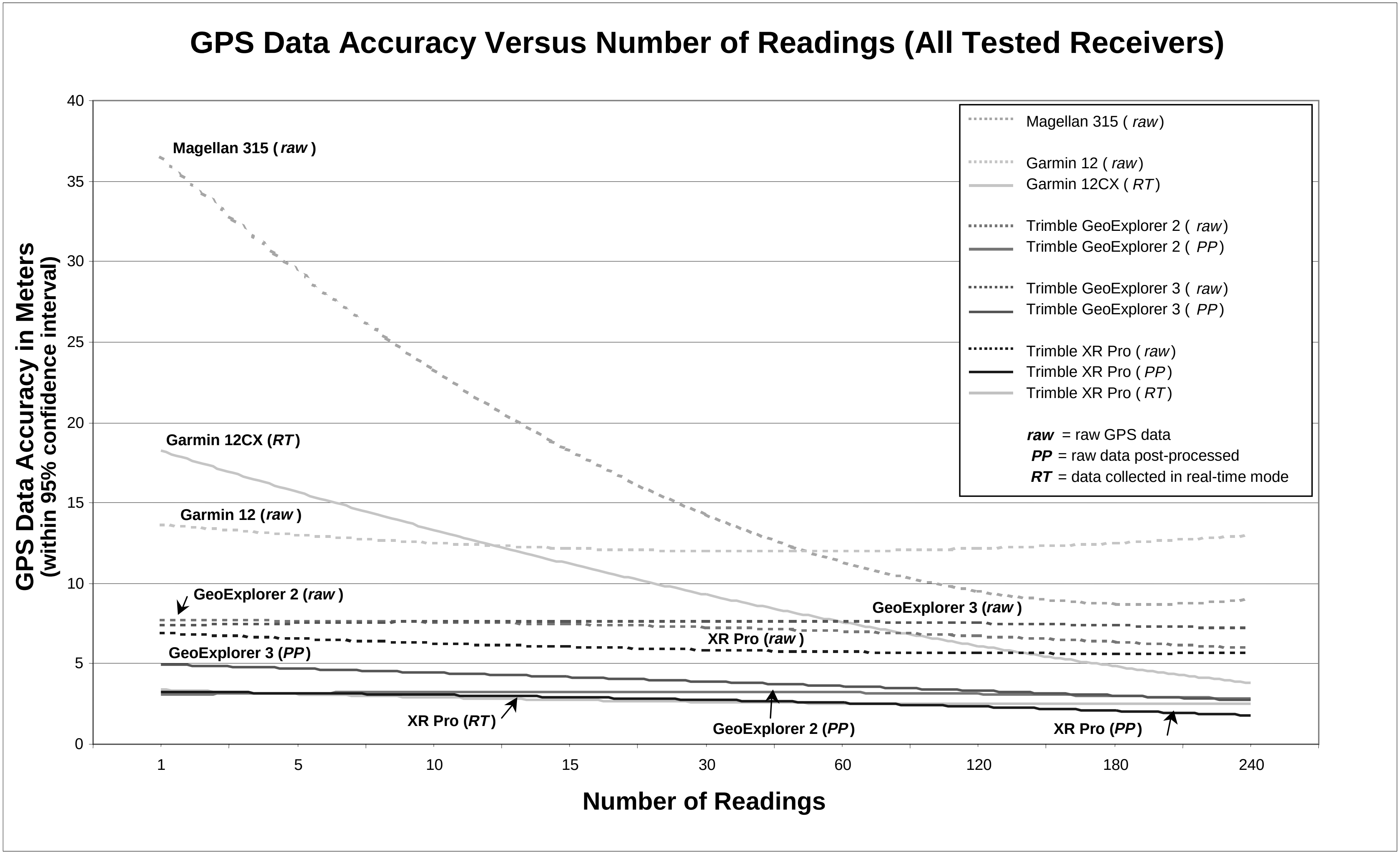
CORS ID	LOCATION	NGS BENCHMARK
BLRW	Blue River, WI	Used to differentially correct data for all 26 benchmarks

The following NGS CORS base stations were used for post-processing differential correction of data used in the following analysis: GPS Data Accuracy and Base Station Selection (***Section III.5***).

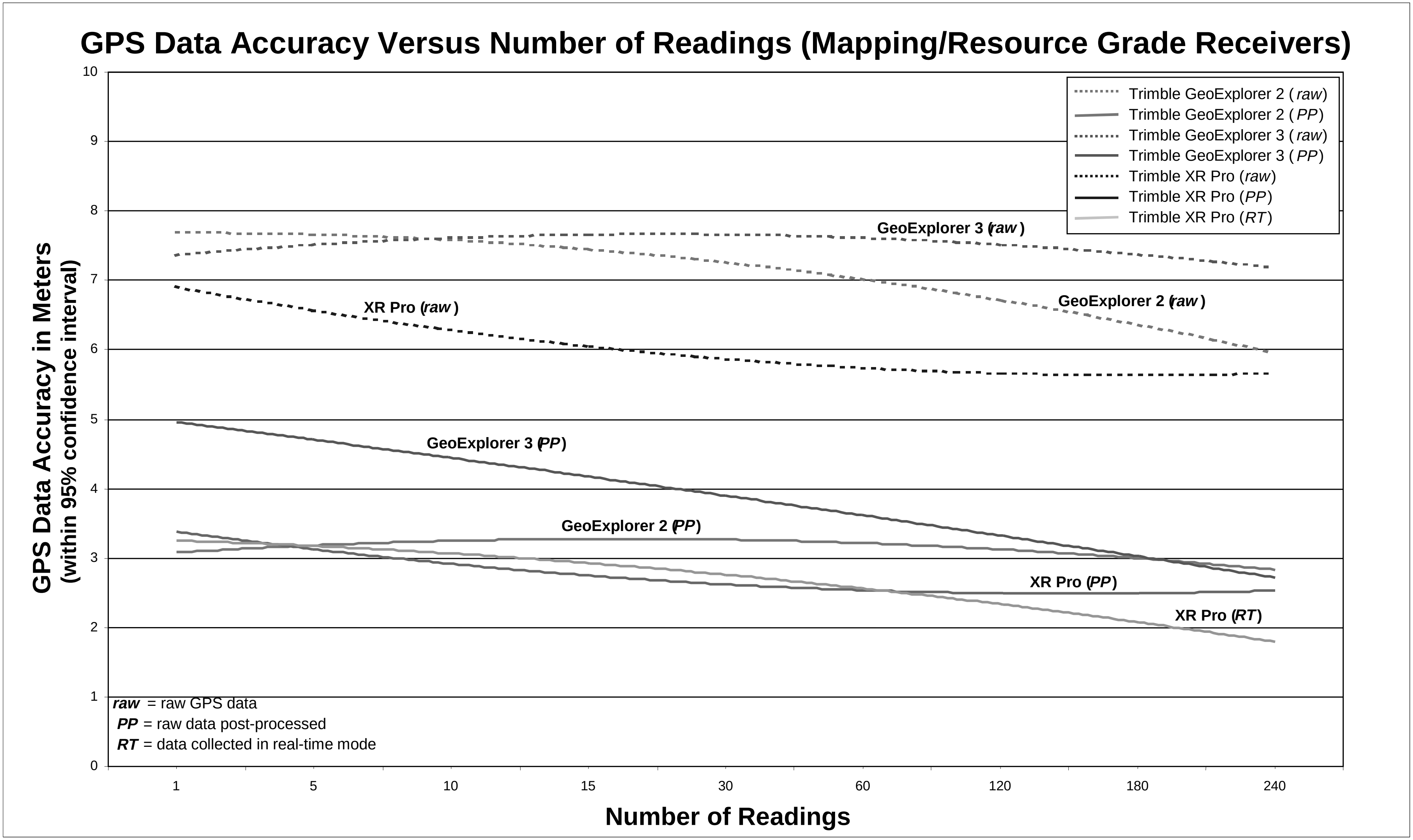
DNR CODE	NGS PID	USGS 7.5' QUAD NAME	LOCATION	APPROXIMATE DISTANCE FROM MADISON, WI
BLRW	AI2149	Blue River	Blue River, WI	58 miles
MIL1	AA8061	Milwaukee	Milwaukee, WI	78 miles
NLIB1	AA3921	Ely	North Liberty, IA	144 miles
RIS1	AE2268	Savanna	Rock Island, IA	84 miles
SLAT1	AI2153	Slater	Slater, IA	236 miles
STB1	AA8057	Sturgeon Bay East	Green Bay, WI	160 miles
WLCI	AH5611	Wolcott	Wolcott, IN	198 miles
*	*	*	Urbana-Champaign, IL	251 miles

* The University of Illinois runs this non-CORS base station.

APPENDIX E: ***GRAPH 1. Data Accuracy for All Receivers Versus Number of Readings.***



APPENDIX E: ***GRAPH 2. Data Accuracy for Mapping/Resource Receivers Versus Number of Readings.***



APPENDIX E: ***TABLE 3. Summary Statistics for All Tested Receivers Versus Number of Readings.***

Recreational Grade GPS

Magellan 315 (*raw*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	21.21	36.71	3.11
5 readings	17.36	30.05	2.82
10 readings	12.86	22.26	2.39
15 readings	9.90	17.14	2.13
30 readings	8.96	15.51	1.96
60 readings	6.61	11.44	1.75
120 readings	2.57	9.75	1.49
180 readings	5.08	8.80	1.35
240 readings	5.02	8.68	1.38

Garmin 12 (*raw*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	8.52	14.75	5.64
5 readings	7.06	12.22	4.93
10 readings	6.40	11.07	3.86
15 readings	7.29	12.62	4.92
30 readings	7.04	12.19	4.82
60 readings	7.08	12.26	4.52
120 readings	7.57	13.10	4.81
180 readings	7.06	12.22	4.79
240 readings	7.25	12.55	4.82

Garmin 12CX (*RT*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	12.33	21.35	2.19
5 readings	7.02	12.15	1.00
10 readings	6.19	10.71	0.71
15 readings	6.88	11.91	1.16
30 readings	6.59	11.40	1.09
60 readings	6.15	10.64	0.58
120 readings	2.05	3.56	1.05
180 readings	2.55	4.41	1.27
240 readings	2.30	3.99	1.18

Mapping/Resource Grade GPS

Trimble GeoExplorer 2 (*raw*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	4.45	7.70	2.24
5 readings	4.39	7.60	2.29
10 readings	4.37	7.56	2.33
15 readings	4.36	7.55	2.31
30 readings	4.21	7.28	2.09
60 readings	4.04	6.99	1.98
120 readings	3.85	6.66	1.97
180 readings	3.66	6.33	1.82
240 readings	3.47	6.01	1.75

Trimble GeoExplorer 3 (*raw*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	4.37	7.56	2.14
5 readings	4.24	7.35	2.17
10 readings	4.27	7.39	2.19
15 readings	4.39	7.59	2.29
30 readings	4.65	8.05	2.56
60 readings	4.31	7.45	2.20
120 readings	4.40	7.61	2.35
180 readings	4.24	7.33	2.36
240 readings	4.13	7.14	2.28

Trimble XR Pro (*raw*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	3.99	6.91	2.35
5 readings	3.71	6.43	2.02
10 readings	3.72	6.45	2.06
15 readings	3.55	6.14	1.87
30 readings	3.34	5.78	1.67
60 readings	3.27	5.67	1.65
120 readings	3.26	5.64	1.65
180 readings	3.27	5.66	1.65
240 readings	3.28	5.68	1.66

Trimble GeoExplorer 2 (*PP*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	1.92	3.33	1.44
5 readings	1.61	2.79	1.16
10 readings	1.92	3.32	1.59
15 readings	2.00	3.46	1.60
30 readings	1.72	2.98	1.31
60 readings	1.76	3.05	1.33
120 readings	2.16	3.74	1.68
180 readings	1.65	2.85	1.26
240 readings	1.57	2.71	1.19

Trimble GeoExplorer 3 (*PP*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	2.84	4.91	1.51
5 readings	2.75	4.76	1.37
10 readings	2.51	4.35	1.07
15 readings	2.42	4.18	1.00
30 readings	2.45	4.24	1.09
60 readings	1.95	3.38	0.98
120 readings	1.88	3.25	1.01
180 readings	1.70	2.94	0.95
240 readings	1.64	2.83	0.93

Trimble XR Pro (*PP*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	1.82	3.16	1.45
5 readings	1.77	3.07	1.42
10 readings	1.87	3.23	1.49
15 readings	1.83	3.17	1.49
30 readings	1.69	2.92	1.37
60 readings	1.33	2.30	1.00
120 readings	1.19	2.07	0.85
180 readings	1.17	2.03	0.87
240 readings	1.15	2.00	0.88

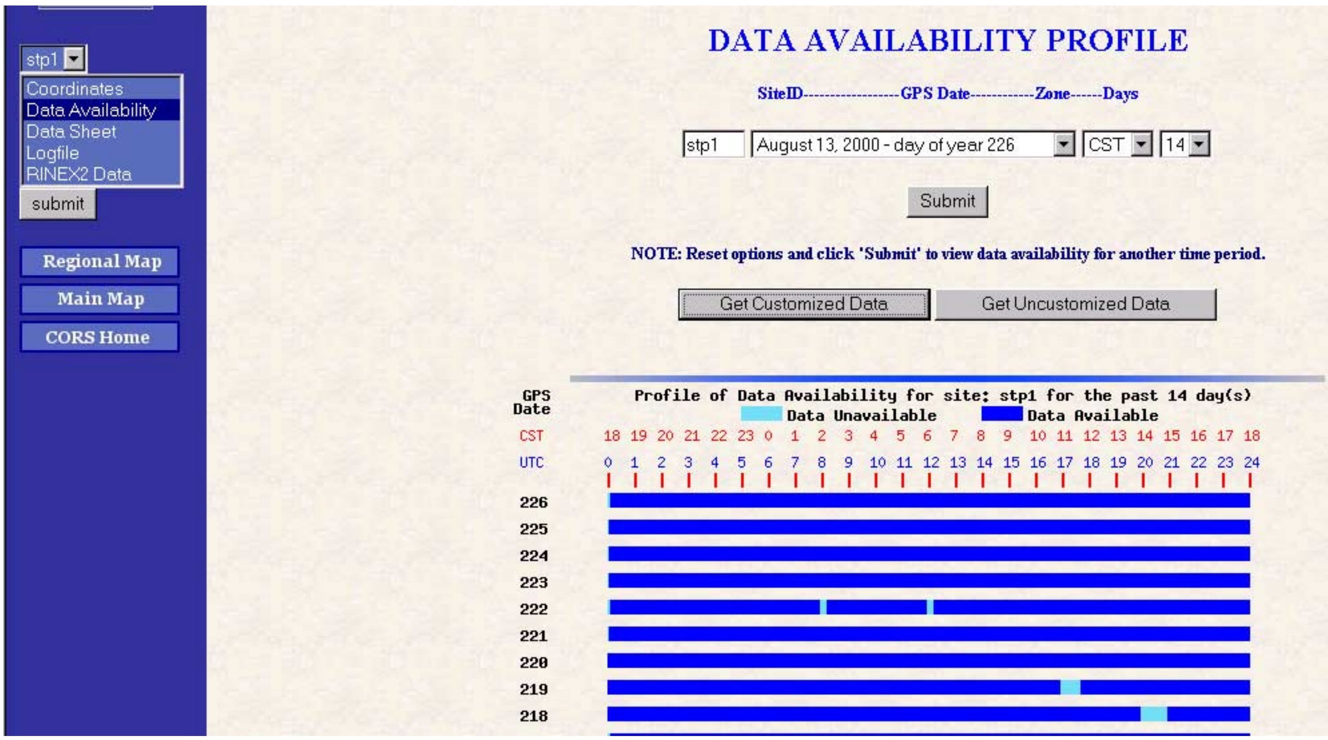
Trimble XR Pro (*RT*)	RMS Error (meters)	95% Conf. Interval (meters)	Standard Deviation (meters)
1 reading	2.08	3.60	1.51
5 readings	1.71	2.96	0.20
10 readings	1.57	2.71	0.99
15 readings	1.55	2.69	1.00
30 readings	1.54	2.67	1.01
60 readings	1.54	2.67	1.02
120 readings	1.52	2.63	1.01
180 readings	1.44	2.50	0.96
240 readings	1.39	2.41	0.93

We used the formulas from the Minnesota Land Management Information Center's *Positional Accuracy Handbook* (1999) to calculate RMS error, 95% confidence interval, and standard deviation. These formulas are presented in **Appendix C**.

APPENDIX F: CHECKING CORS BASE STATION AVAILABILITY

You can check the availability of base stations via the CORS website: http://www.ngs.noaa.gov/CORS/ following these steps:

1. Click Wisconsin on the map at the bottom of the CORS homepage.
2. Click on the selected base station.
3. Select "Data Availability" in the menu box at the left of the map, and then click the "submit" button.
4. The "Data Availability Profile" page asks you to enter the *GPS Date* (i.e., date range to include in the profile), *Zone* (i.e., Wisconsin is in the Central Standard Time Zone or CST), and *Days* (i.e., number of days to include in the profile) for the selected base station. The resulting graph shows you the when the selected CORS base station was operational.



Please note the following characteristics:

- Light blue areas indicate time blocks when selected CORS data were unavailable, which means that data from the station can't be used for differential correction.
- *GPS Date* is listed in Julian days. For example, day 226 equals August 13, 2000.
- Time is measured in 24 one-hour blocks. For example, block 18 to 19 equals 6:00 through 6:59pm.